

An Improved Elastic and Nonelastic Neutron Transport Algorithm for Space Radiation

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**International Workshop on Secondary Particle Production from
Heavy Ion Interactions**

Lawrence Berkeley National Laboratory, Berkeley, California
March 15-16, 2001

The HZETRN Transport Code

- Calculates particle transport deterministically using approximate solutions to the Boltzmann transport equation
- Is much faster than Monte Carlo codes
- Can be used to calculate the transport of heavy ions as well as light ions and neutrons

Boltzmann Transport Equation

$$\begin{aligned}\Omega \bullet \nabla \phi_j(x, \Omega, E) = & \\ & \Sigma \int \sigma_{jk}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ & - \sigma_j(E) \phi_j(x, \Omega, E)\end{aligned}$$

Boltzmann Equation

$$\begin{aligned}\Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \int \sigma_{jk}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E)\end{aligned}$$

$\phi_j(x, \Omega, E)$ represents the flux density of type j particles moving in direction Ω with energy E

$\sigma_j(E)$ is the media macroscopic cross section for removal of type j particles of energy E

$\sigma_{jk}(\Omega, \Omega', E, E')$ are the media macroscopic cross sections for various atomic and nuclear processes adding type j particles of energy E in direction Ω

Expanding Solutions

$$\sigma_j(E) = \sigma_{j,at}(E) + \sigma_{j,el}(E) + \sigma_{j,r}(E)$$

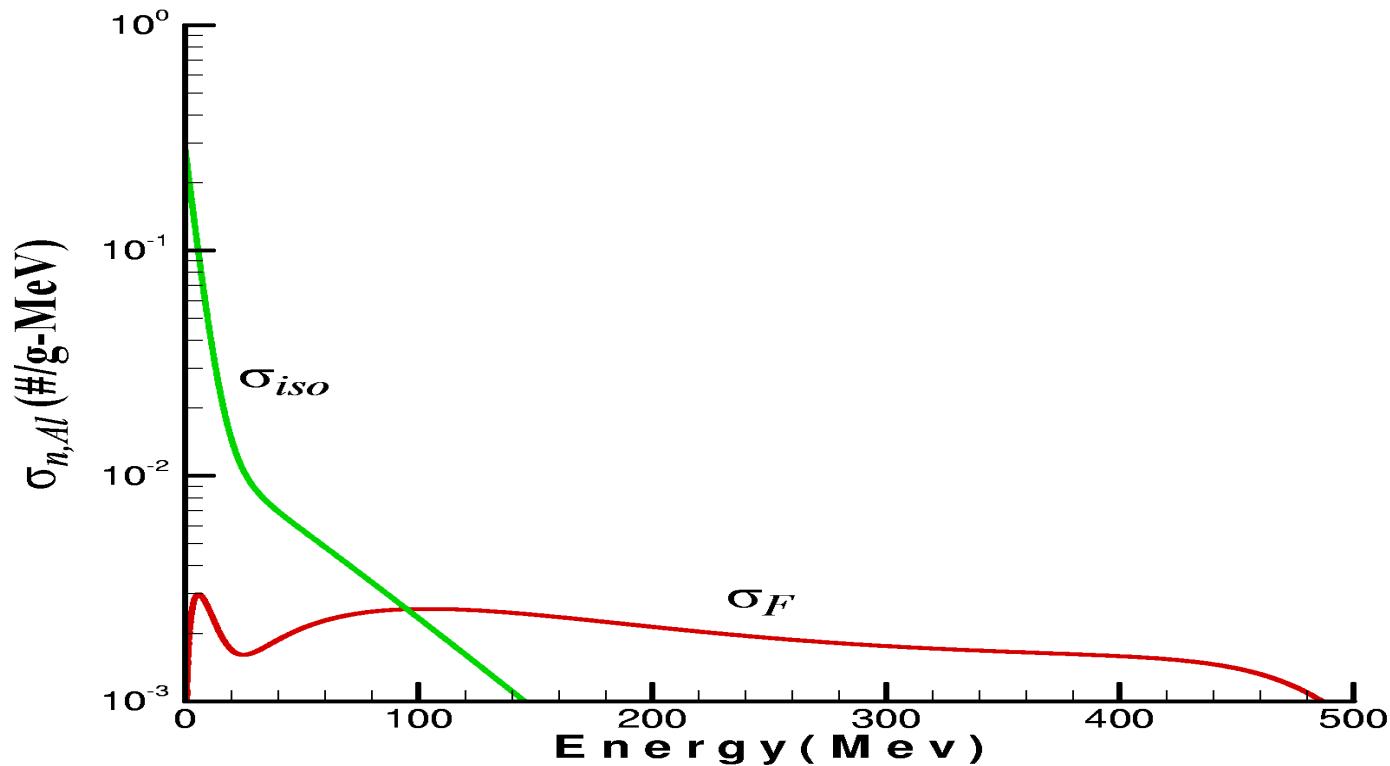
Separation of Straight Ahead and Isotropic Particle Production

$$\sigma_{jk}(\Omega, \Omega', E, E') = \sigma_F + \sigma_{iso}$$

σ_F consists of forward directed secondary particles

σ_{iso} is dominated by low energy neutrons

Forward Moving and Isotropic Neutron Spectral Effects for Collision of 500 MeV Neutrons in Aluminum



Two Coupled Boltzmann Equations

$$(1) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \sum \sigma_F(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' - \sigma_j(E) \phi_j(x, \Omega, E)$$

and

$$(2) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \sum \sigma_{iso}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' - \sigma_j(E) \phi_j(x, \Omega, E) + g(x, E)$$

The Isotropic Neutron Source Term

$$g(x, E) = \sum \sigma_{iso}(\Omega, \Omega', E, E') \phi_F(x, \Omega', E') d\Omega' dE'$$

where $\phi_F(x, \Omega', E')$ is the solution to equation (1)

$$(1) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \sum \sigma_F(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E)$$

$$(2) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \sum \sigma_{iso}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E) + g(x, E)$$

Solution to Equation (1)

- Straight ahead approximation used in current version
- Approximate perturbation type solution found

$$(1) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \sum \sigma_F(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E)$$

$$(2) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \sum \sigma_{iso}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E) + g(x, E)$$

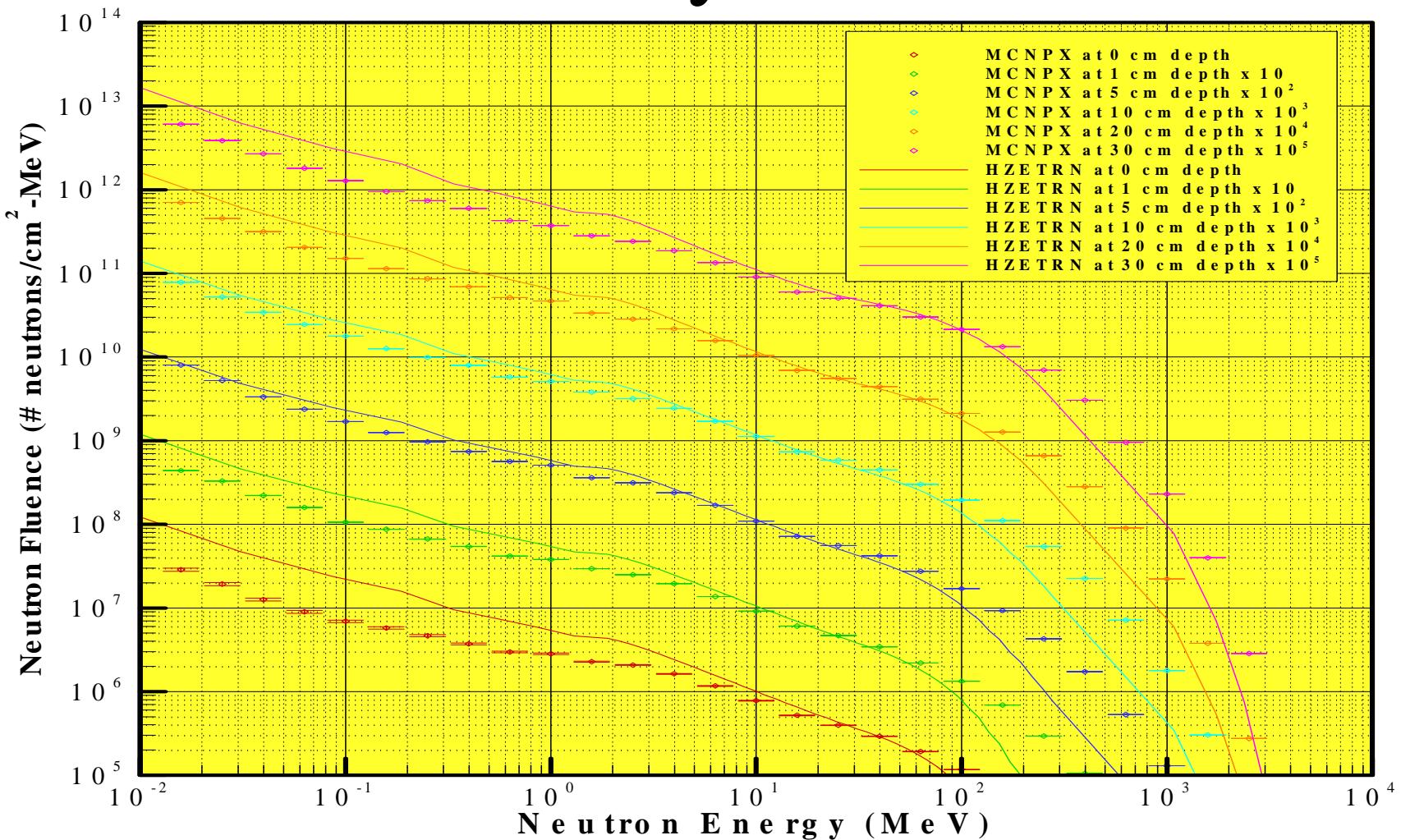
Solution to Equation (2)

- A modified multigroup method used
- Each term of equation (2) integrated over a small energy interval for a finite number of energy intervals
- Multigroup integrals evaluated using an integral mean value theorem
- Half of the source neutrons propagated in the forward direction and half in the backward direction

$$(1) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \Sigma \int \sigma_F(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E)$$

$$(2) \quad \Omega \bullet \nabla \phi_j(x, \Omega, E) = \\ \Sigma \int \sigma_{iso}(\Omega, \Omega', E, E') \phi_k(x, \Omega', E') d\Omega' dE' \\ - \sigma_j(E) \phi_j(x, \Omega, E) + g(x, E)$$

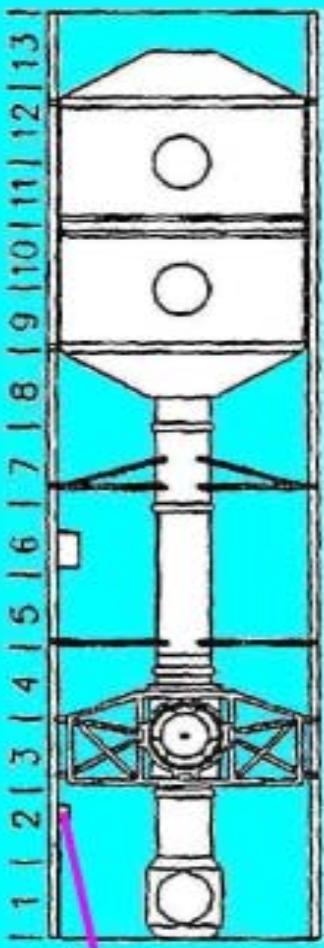
Neutron Fluence in a Water Slab for the February 23, 1956 SPE



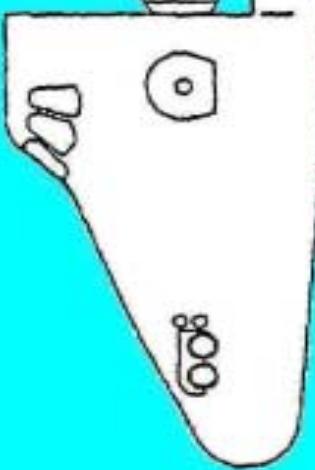
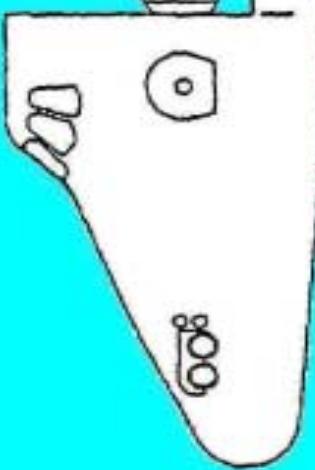
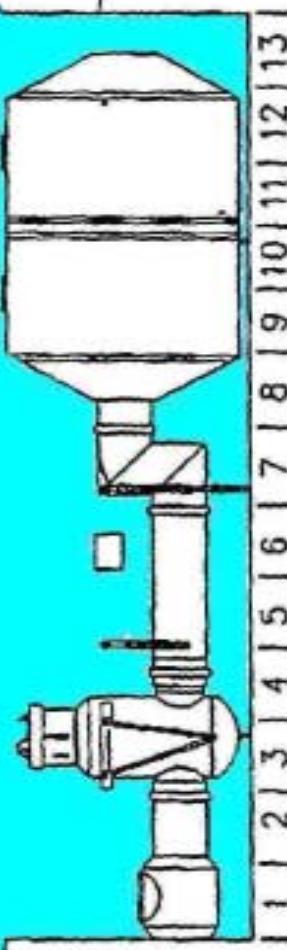
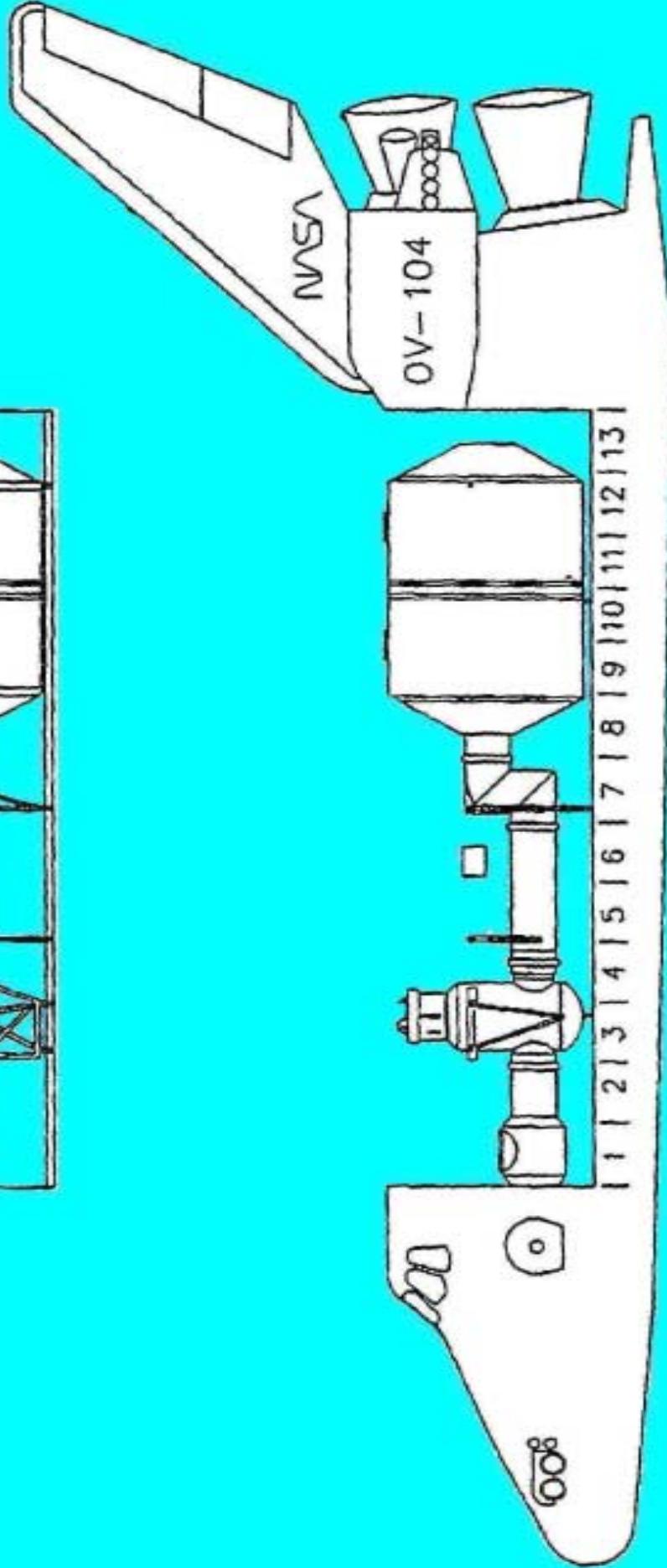
Low Earth Orbit Radiation Environment

- Galactic Cosmic Rays (GCR)
- Particles trapped in the Earth's magnetic field (primarily protons)
- Neutrons produced as secondaries in interaction of the GCR with the Earth's atmosphere (albedo neutrons)

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Dosimetry
Location 8

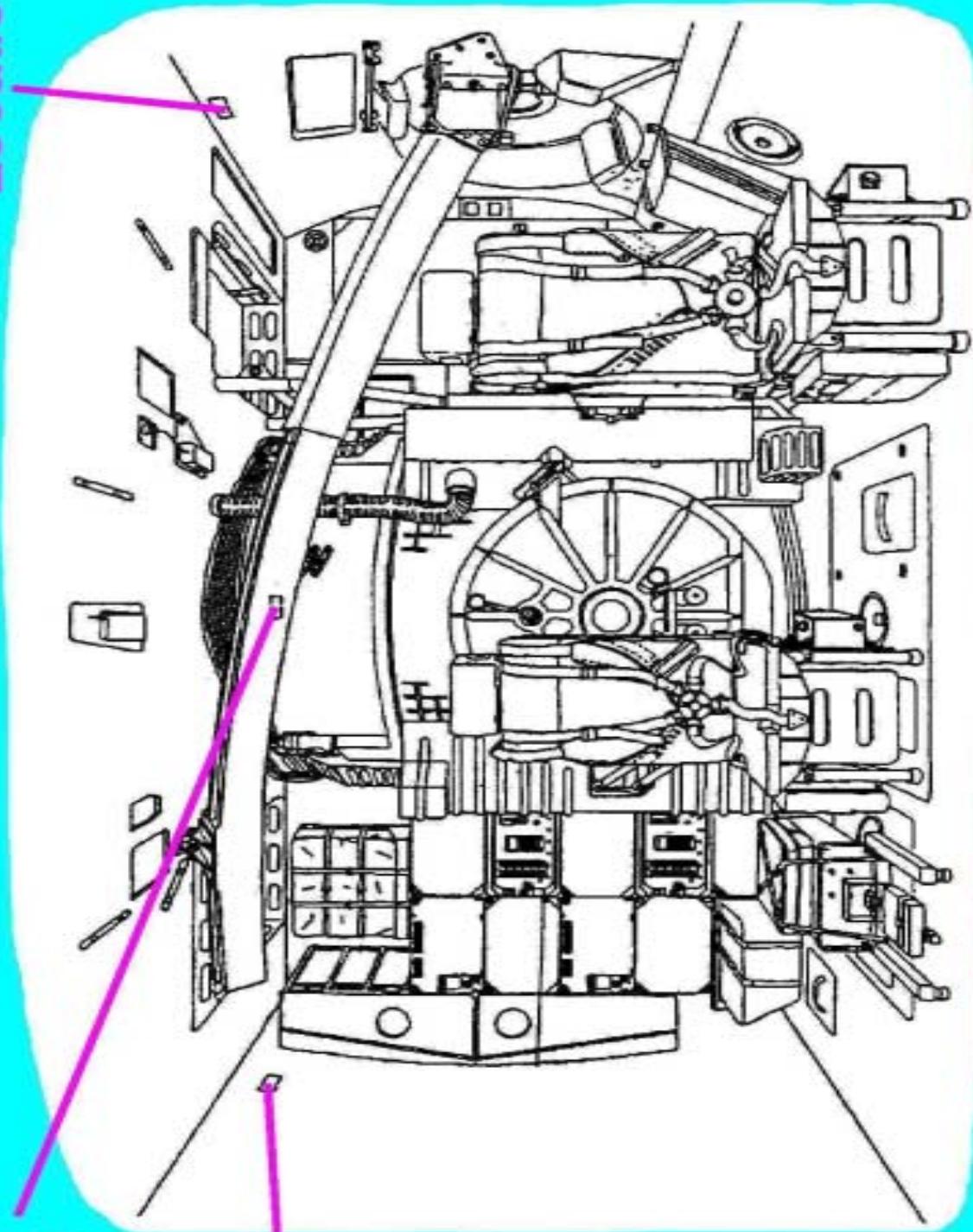


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Dosimetry
Location 3

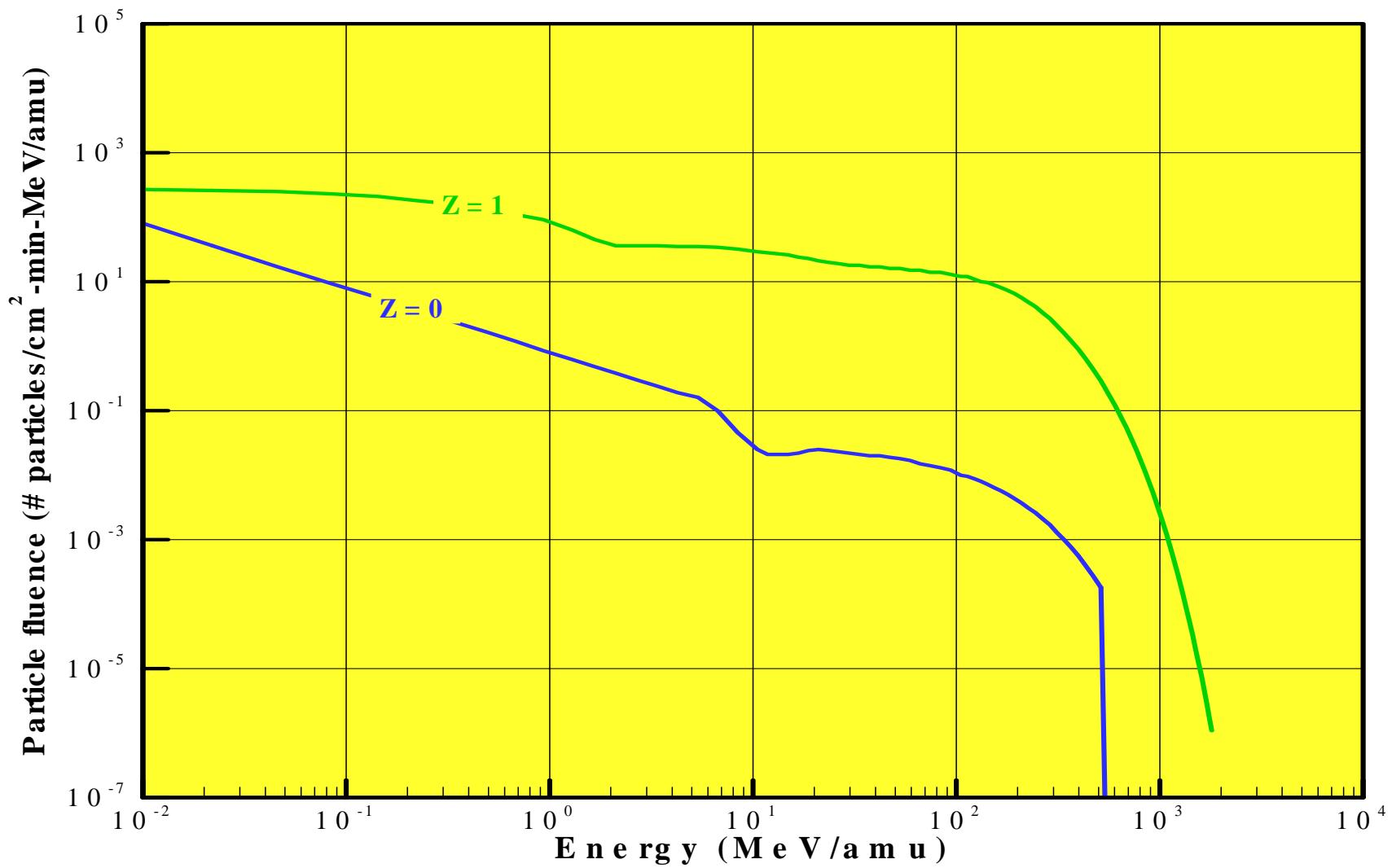
Dosimetry
Location 1

Dosimetry
Location 2



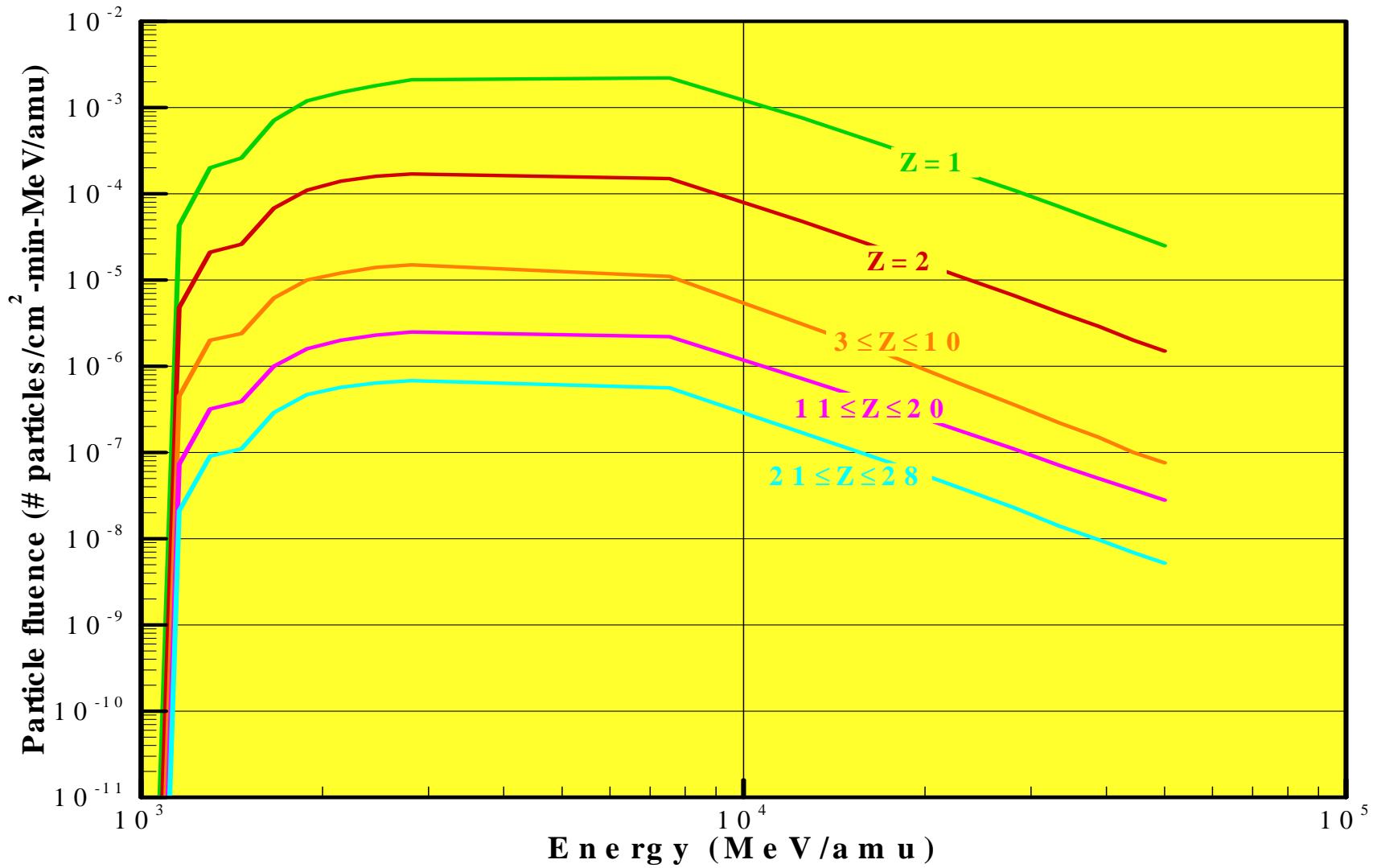
Trapped Particle Environment

STS-31, 28.5° - 617 km orbit, April 1990



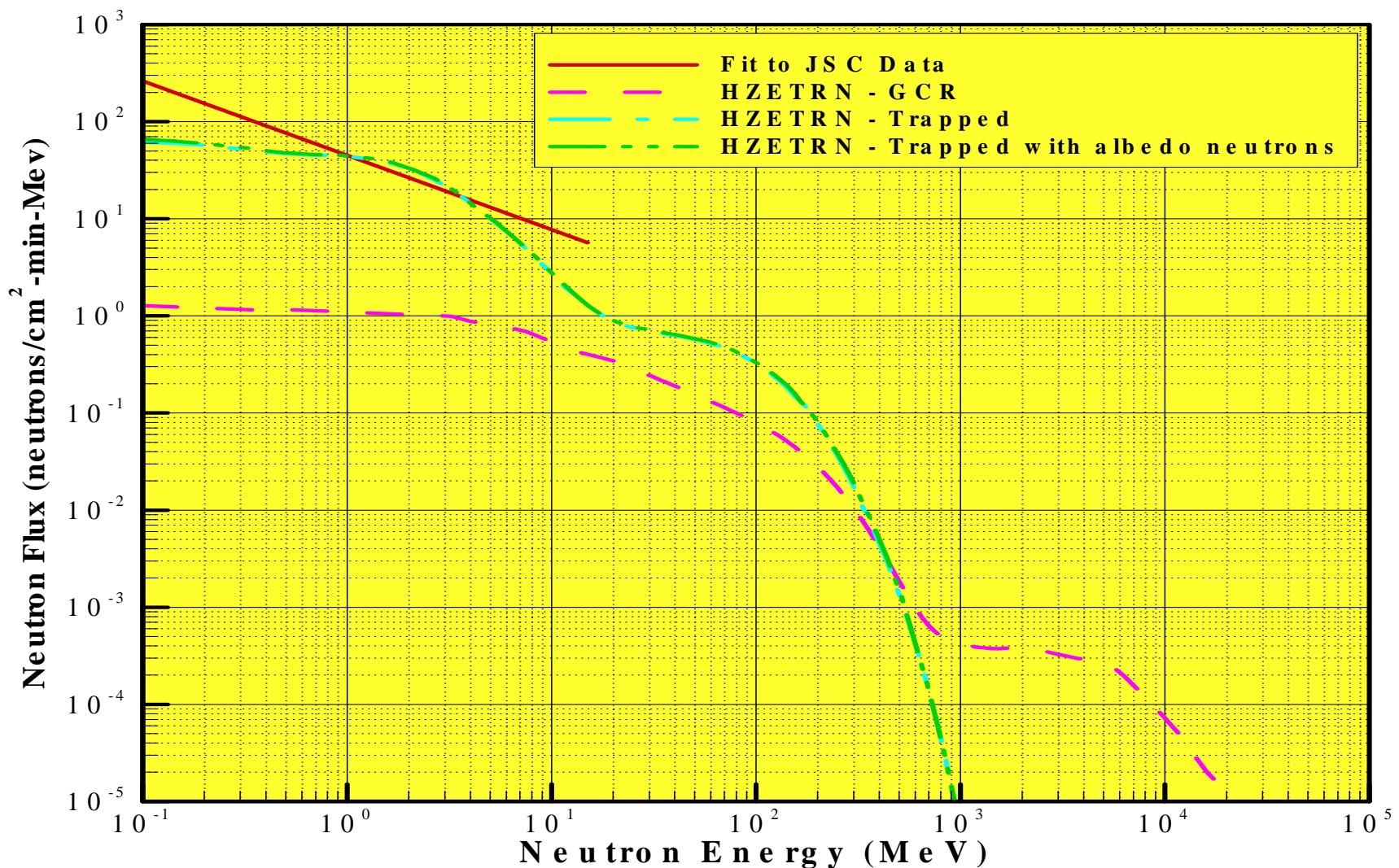
GCR Environment

STS-31, 28.5° - 617 km orbit, April 1990



Shuttle Neutron Measurements

STS-31, 28.5° - 617 km orbit, April 1990



Shuttle Dose Calculations

STS-31, 28.5° - 617 km orbit, April 1990

Daily dose due to trapped radiation:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	0.254	0.382
Eye	0.252	0.357
BFO	0.161	0.230

Daily dose due to trapped radiation without neutrons:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	0.254	0.375
Eye	0.251	0.348
BFO	0.160	0.223

Shuttle Dose Calculations

STS-31, 28.5° - 617 km orbit, April 1990

Daily dose due to GCR radiation:

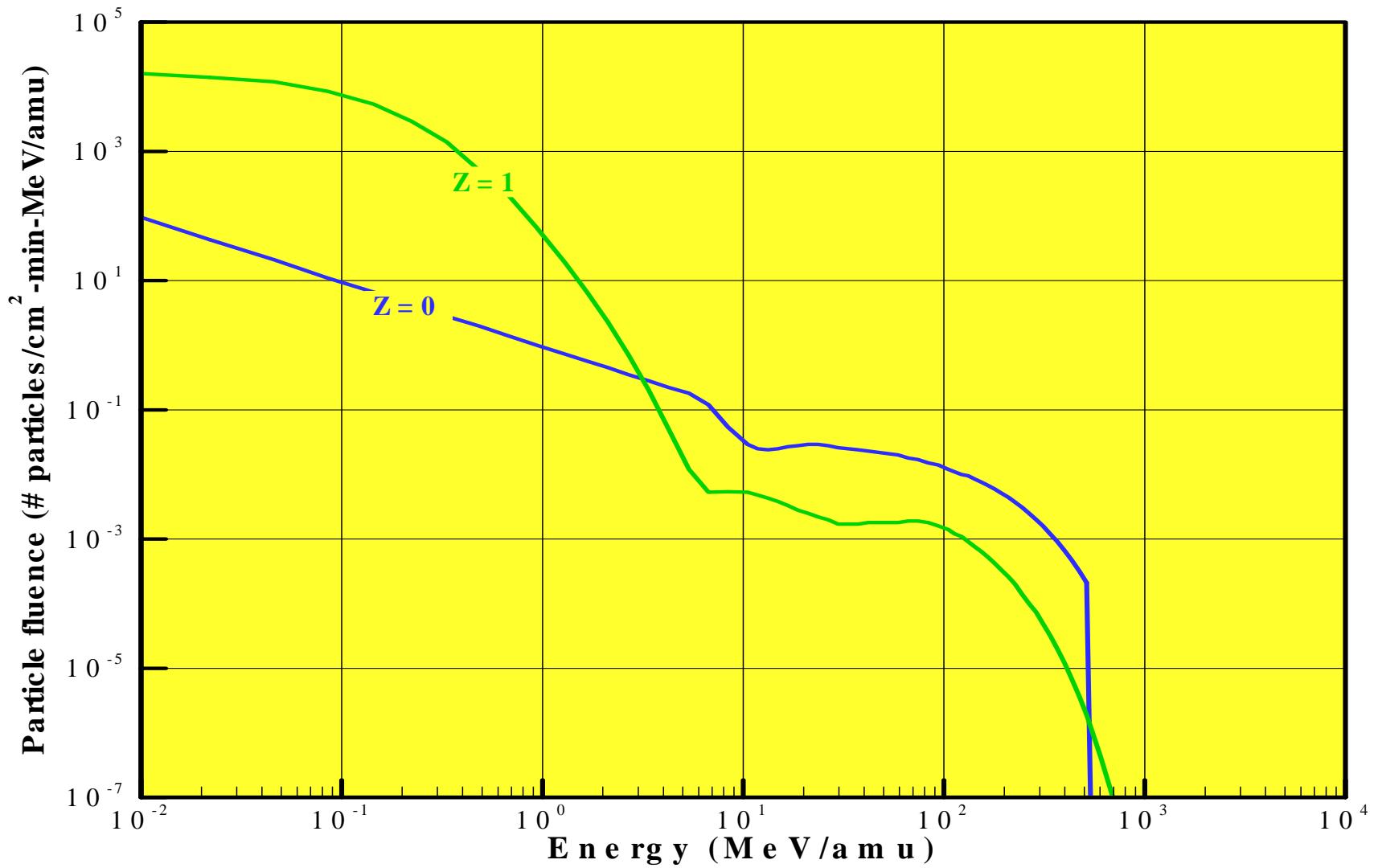
	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	4.10E-03	1.45E-02
Eye	4.02E-03	1.39E-02
BFO	4.04E-03	1.25E-02

Daily dose due to GCR radiation without neutrons:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	3.91E-03	1.32E-02
Eye	3.78E-03	1.23E-02
BFO	3.75E-03	1.11E-02

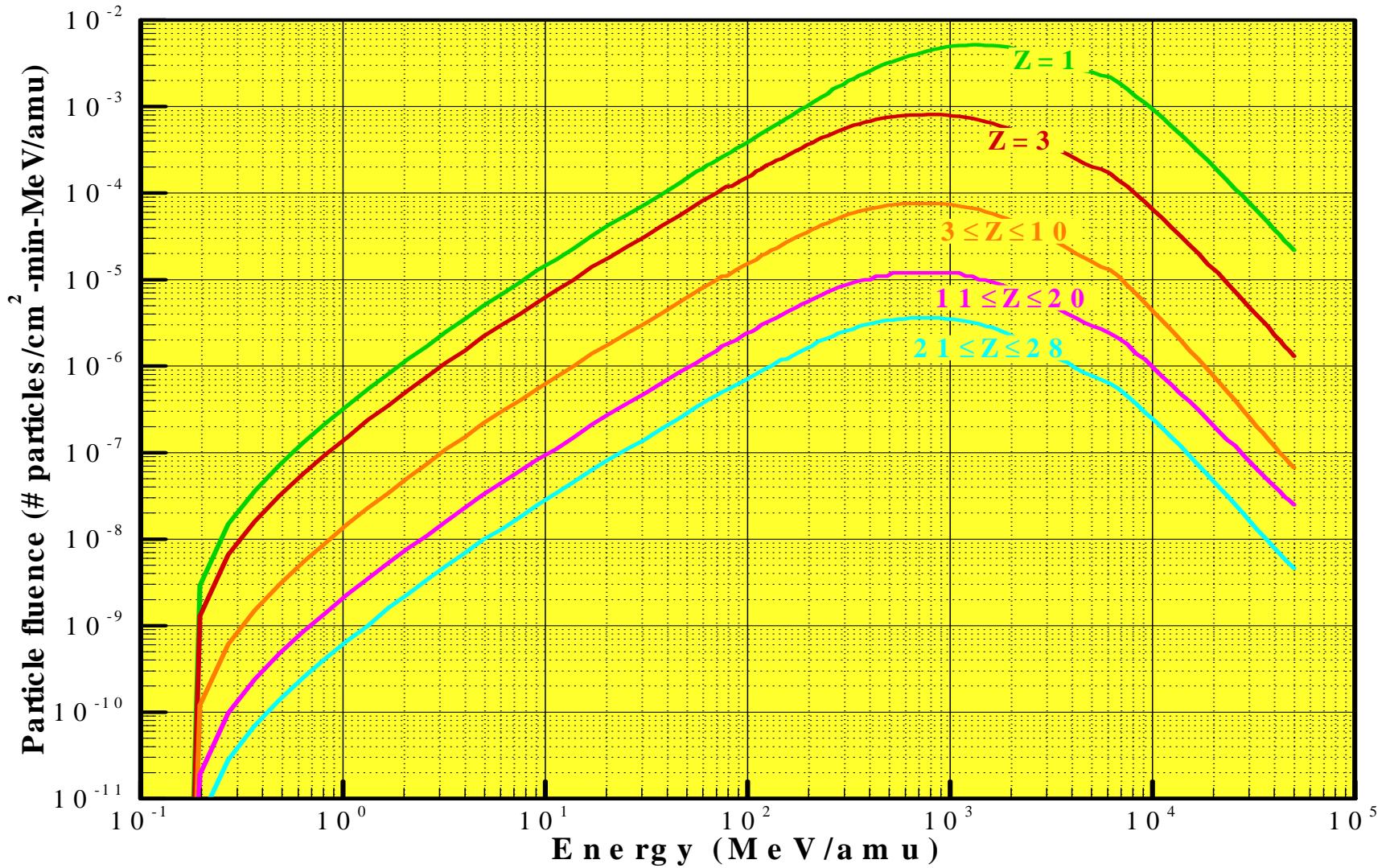
Trapped Particle Environment

STS-36, 62° – 246 km orbit, Feb/March 1990



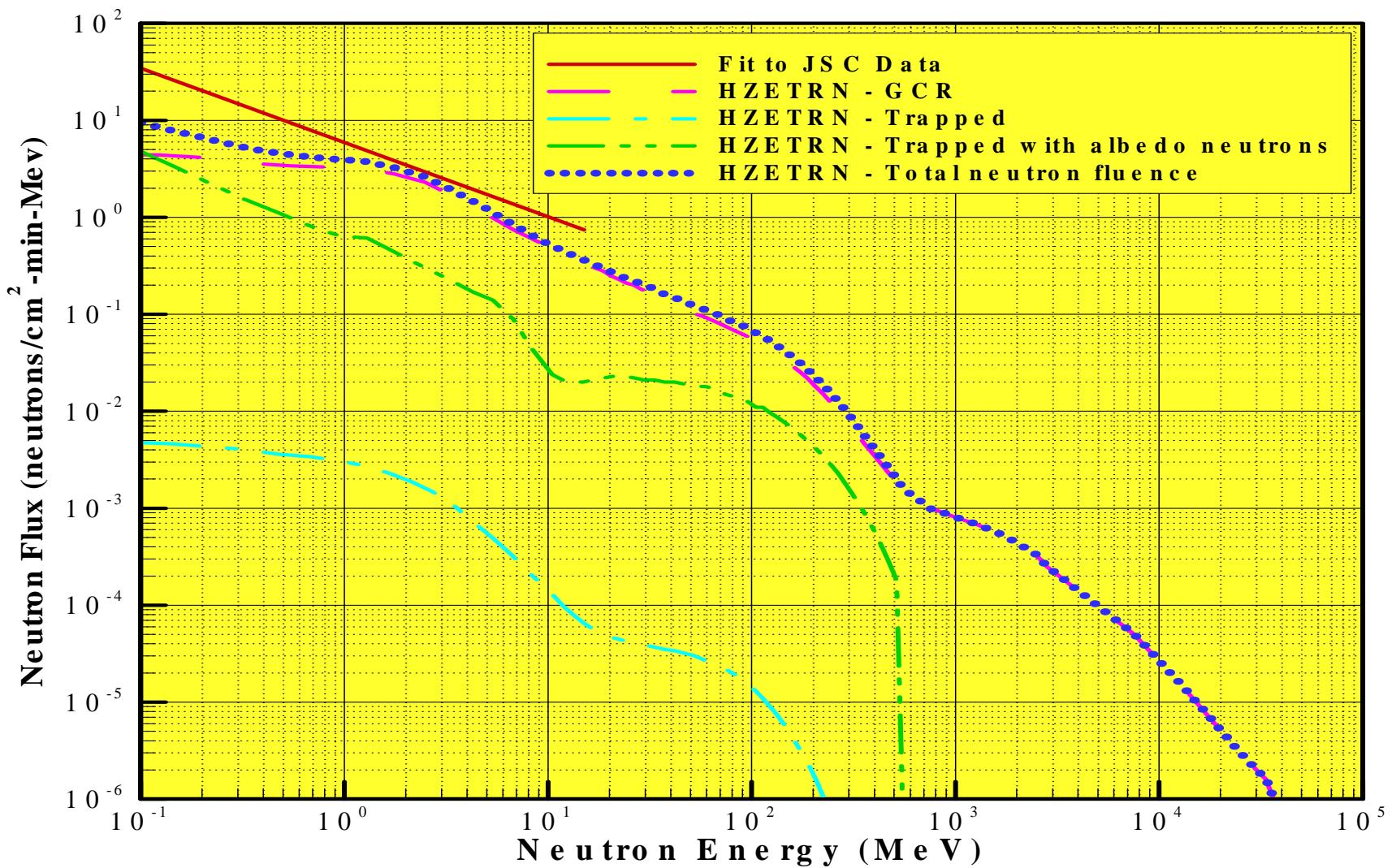
GCR Environment

STS-36, 62° – 246 km orbit, Feb/March 1990



Shuttle Neutron Measurement

STS-36, 62° – 246 km orbit, Feb/March 1990



Shuttle Dose Calculations

STS-36, 62° – 246 km orbit, Feb/March 1990

Daily dose due to trapped radiation:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	6.37E-05	3.11E-04
Eye	6.50E-05	3.09E-04
BFO	5.91E-05	2.44E-04

Daily dose due to trapped radiation without neutrons:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	3.22E-05	8.91E-05
Eye	2.74E-05	3.92E-05
BFO	1.21E-05	1.67E-05

Shuttle Dose Calculations

STS-36, 62° – 246 km orbit, Feb/March 1990

Daily dose due to GCR radiation:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	5.56E-03	2.19E-02
Eye	5.46E-03	2.14E-02
BFO	5.43E-03	1.84E-02

Daily dose due to GCR radiation without neutrons:

	<u>Dose (cGy)</u>	<u>Dose Equivalent (cSv)</u>
Skin	5.34E-03	2.05E-02
Eye	5.19E-03	1.95E-02
BFO	5.09E-03	1.67E-02

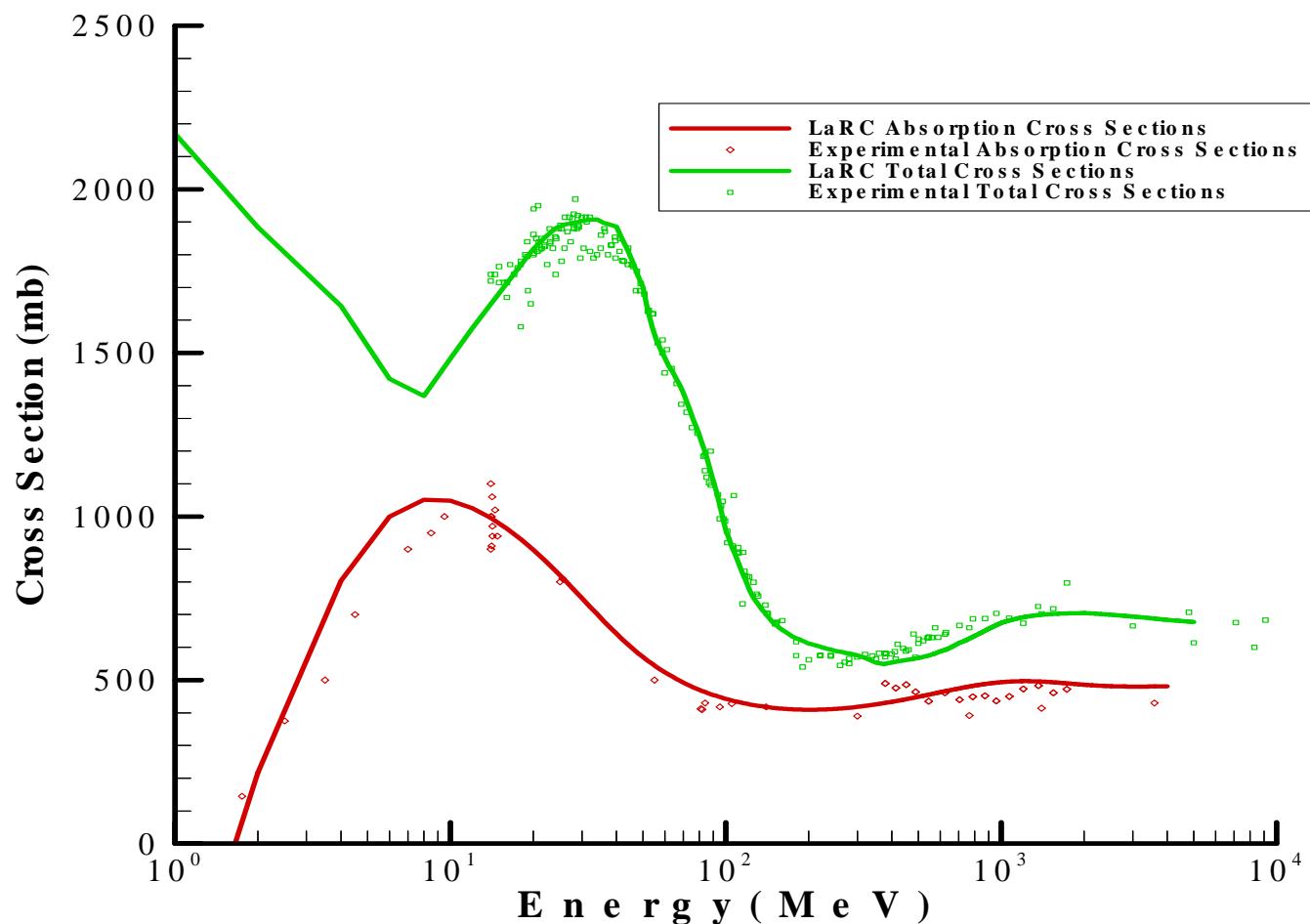
International Space Station



Improved Nuclear Interaction Models

Aluminum Cross Sections as a Function of Neutron Energy

(media modified two-body amplitudes in quantum scattering theory)



Summary

- The coupling of neutrons to the ion fields has been the focus of research over the last several years
- New transport methods that take into account the isotropic nature of low energy neutrons have been developed
- These transport procedures predict neutron fluence more accurately

Summary (Continued)

- These deterministic transport methods are much faster than Monte Carlo methods
- Shuttle calculations show that neutrons contribute significantly to dose
- For long term missions such as the International Space Station the production of secondary neutrons in shielding material must not be ignored